VLQ searches and hadronic final states - CMS

Antimo Cagnotta (Univ. & INFN Napoli) on behalf of CMS collaboration
Contents

- Introduction to BSM searches

- $T \rightarrow tH \ (H \rightarrow \gamma \gamma)$ B2G-21-007 (submitted to JHEP, arxiv 2302.12802)

- Pair production $TT/BB$ B2G-20-011 (accepted by JHEP, arxiv 2209.07327)


- Conclusions
BSM searches

- **New Physics searches** → look for new particles predicted by beyond SM theories
- rare final states or high-centre-of-mass energy $\sqrt{s}$ needed!

**Vector-Like Quarks**

- Vector-like quarks (VLQ): colored 1/2-spin particles, left and right components are symmetric
- VLQ masses do not depend on Yukawa couplings
- Predicted by many theoretical models
- Can be produced at LHC
  - **Pair production** via Strong interaction
    - $\sigma$ does not depend on VLQ $\Gamma$ and EW coupling
  - **Single production** via EW interaction
    - heavier masses can be probed

**Hadronic final states**

- Decays to heavy SM objects, $H/W/Z/\text{Top}$:
  - High $\sqrt{s}$ → large Lorentz boost
- **Large BR** in hadronic decays → **large background** (multijet)
- Focus on diboson final state
  - can be produced by
    - **spin-0 Rad** and **spin-2 $G_{bulk}$** in the Randall–Sundrum model with warped extra dimensions
    - **spin-1** vector boson resonances ($W'$ and $Z'$) appearing in composite Higgs and little Higgs models

**Leptonic final states** in Halil and Nicolas’ talks

**New Physics searches**

- look for new particles predicted by beyond SM theories
- rare final states or high-centre-of-mass energy $\sqrt{s}$ needed!
Vector-Like Quarks (VLQs)

- In minimal models, VLQs exist as either singlets (T and B) or as a doublet (T, B), each with different Branching Fractions:
  - singlet → 50% (T → bW, B → tW),
    25% (T → tH and → tZ, B → bW and → bZ)
  - doublet → 50% (T → tH and → tZ, B → bW and → bZ)
\( T \rightarrow tH \ (H \rightarrow \gamma \gamma) \)

- EW single production of an isospin singlet VLQ T
- NWA \( \rightarrow \Gamma \approx 1\% \) of \( M_T \) (valid up to \( \frac{\Gamma}{M_T} \approx 10 - 15\% \))

- Search in \( tH \) final state
  - diphoton reconstruction of \( H \)
  - \( t \rightarrow Wb \) separately considered: \( W \rightarrow l\nu \) and \( W \rightarrow q\bar{q}' \)

- Selection:
  - 2 prompt photons
    - leptonic events \( \rightarrow 1 \) electron/muon
    - hadronic events \( \rightarrow 2 \) jets
  - + 1 b-tagged jet
$T \rightarrow tH \; (H \rightarrow \gamma \gamma)$

- **Background composition:**
  - **Leptonic category:** Drell-Yan processes
  - **Hadronic category:** QCD and $\gamma(\gamma) + jets$
  - Both categories: dominant background $ttH$, among the SM Higgs (SMH) production processes
  - BDT-SMH implemented separately for each category
  - Additional BDT (BDT-NRB) suppresses Non-Resonant Backgrounds in the hadronic category

- **Signal extraction via fit to $m_H$:**
  - Exploits $m_{\gamma\gamma}$ resolution of 1-2%
  - Searches for a peak in the invariant mass of the reconstructed photons

- No significant excess found in data
$T \to tH \ (H \to \gamma \gamma)$

- With $\kappa_T = 0.25$ and a width of $\Gamma/M_T < 5\%$, the search has successfully excluded the EW production of a singlet $T'$ VLQ up to a mass of 960 GeV at a 95% CL.
Pair production $TT/BB$

- Assumptions:
  - Only one flavor of VLQ is present in this search

- Three final states considered
  - **single-lepton channel** ($1 \ell$)
  - **same-sign charge (SS) dilepton channel** ($2 \ell$)
  - **multilepton channel with at least three leptons** ($\geq 3 \ell$)
Pair production $TT/BB$

**Single-lepton channel**

- Provides broad sensitivity to all $T\bar{T}$ decays, as well as to $B \rightarrow tW$
- A VLQ pairs decay produce 2 top or bottom quarks and 2 $W, Z, or H$ bosons
- Final state: 1 top or $W$ decays in $\rightarrow l\nu$, while the other products decay hadronically in $\geq 3$ large-radius jets (AK8)

- $\ell + MET = W$ or $b$-jet $+ W = t$
- $(W/t + AK8), (AK8 + AK8) = VLQ$ pairs
- MLP trained to separate SR and CR
  - 2 independent model for TT and BB
Pair production $TT/BB$

Same-Sign charge (SS) dilepton channel

- sensitive to $T \rightarrow tH$ (with $H \rightarrow WW$) and $B \rightarrow tW$ decays

- $1\ell + 1\nu + 1W - \text{jet}$ and jets from $t$

- $1\ell + 1\nu + \text{jet from } H$
- $t \rightarrow bW, W \rightarrow 1\ell + 1\nu$

Multilepton channel with at least three leptons

- sensitive to $T \rightarrow tZ$ and $B \rightarrow tW$ decays

- $2\ell$ from $Z + 1\ell$ from $W + 1b - \text{jet}$

- $0\text{ to } 3\ell$ from $W/Z/H + 1b - \text{jet}$

- $1 - 2\ell$ from $2W + 1b - \text{jet}$

- $1 - 2\ell$ from $2W$ or $Z + 1b - \text{jet}$
Pair production $TT/BB$

- Simultaneous fit using template histograms from multiple different discriminating variables in all three channels.
- From the scan, we exclude T quarks with masses below 1.48–1.54 TeV and B quarks with masses below 1.12–1.56 TeV, depending on the branching fraction. T masses below 1.48 TeV are excluded in any scenario.
BSM searches

- **New Physics searches** → extend the SM discovering new particles
- rare final states or high-centre-of-mass energy $\sqrt{s}$ needed!

### Vector-Like Quarks

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  - Predicted by many theoretical models
  - Can be produced at LHC
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  - σ heavier mass can be probed
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### Hadronic final states

- Decays to heavy SM objects, $H/W/Z/Top$:
  - High $\sqrt{s}$ → large Lorentz boost
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- **Leptonic final states** in Halil and Nicolas’ talks

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23/05/2023

A. Cagnotta - LHCP2023
Diboson pairs in all-jet final state

- Search for new heavy resonances decaying in diboson pairs
- Resonances produced via gluon fusion (ggF), Drell–Yan (DY), or vector boson fusion (VBF) are targeted in final state made up by 2 large-radius jets (AK8)
- Large-radius jets selection → “groomed” mass and deepAK8 tagger
- Several regions are determined based on the misID of the deepAK8 tagger

<table>
<thead>
<tr>
<th>2 Large-radius jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
</tr>
<tr>
<td>VH (Low</td>
</tr>
<tr>
<td>VV (Low</td>
</tr>
<tr>
<td>ggF/DY</td>
</tr>
<tr>
<td>VH (Low</td>
</tr>
<tr>
<td>VV (Low</td>
</tr>
</tbody>
</table>
Diboson pairs in all-jet final state

- Background composition
  - Non-resonant background (Multijet)
  - Dominant background
  - Forward folding ensures smooth, full spectrum
  - Partially resonant
    - Resonant in $m_{jet1}$ or $m_{jet2}$, non-resonant in $m_{jj}$
    - Model separately $ttbar$ and $V+jets$

- 3D maximum likelihood fit of signal and background templates to data in ($m_{jj}$, $m_{jet1}^{AK8}$, $m_{jet2}^{AK8}$) space is conducted in all regions

- Excess observed:
  - DY/ggF VH category: 1.7–3.2 TeV range
  - DY/ggF VV category: around 2 and 3 TeV

Global significance of 2.3$\sigma$
Upper limits on the production cross section at 95% CL are set

A global significance of $2.3\sigma$ is found under $W' \to WZ$ hypothesis at 2.1 and 2.9 TeV mass

Searches in the semileptonic final states did not observe any excesses in the same mass range
Conclusions

- An overview of recent results in BSM searches is presented
  - VLQs
    - $T \rightarrow tH (\gamma\gamma)$ the most sensitive to date for mass up to 1.1 TeV with this production mechanism
    - TT production strongest limits to date with all decays mode and the BB production strongest limit in $tW$ decay
  - Hadronic final state
    - a diboson pair production in all hadronic final state with an excess found in data is presented. However, searches in the semileptonic final states did not observe any excesses in the same mass range

Unleash the power of Run 3 results!
backup
### VLQ

<table>
<thead>
<tr>
<th>SM</th>
<th>Singlets</th>
<th>Doublets</th>
<th>Triplets</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u_d) (c_s) (t_b)</td>
<td>(t')</td>
<td>(X_{t'}) (t'<em>{b'}) (b'</em>{Y})</td>
<td>(X_{t'}) (t'<em>{b'}) (b'</em>{Y})</td>
</tr>
</tbody>
</table>

#### $SU(2)_L$
- $q_L = 1/6$
- $u_R = 2/3$
- $d_R = -1/3$

#### $U(1)_Y$
- 2 and 1
- 1
- 2
- 3

#### $\mathcal{L}_Y$

<table>
<thead>
<tr>
<th>Term</th>
<th>SM Term</th>
<th>Singlet Term</th>
<th>Doublet Term</th>
<th>Triplet Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-\frac{y_{t\nu}}{\sqrt{2}} \bar{u}_L^i u^i_R$</td>
<td>$-\frac{\Lambda_{t\nu}}{\sqrt{2}} \bar{u}_L^i U_R$</td>
<td>$\frac{\Lambda_{t\nu}}{\sqrt{2}} U_L u^i_R$</td>
<td>$-\frac{\Lambda_{t\nu}}{\sqrt{2}} U_L u^i_R$</td>
<td></td>
</tr>
<tr>
<td>$-\frac{y_{t\nu}}{\sqrt{2}} d^i_v \bar{d}^i_{L R}$</td>
<td>$-\frac{\Lambda_{t\nu}}{\sqrt{2}} \bar{d}^i_{L R}$</td>
<td>$-\frac{\Lambda_{t\nu}}{\sqrt{2}} \bar{d}^i_{L R}$</td>
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$T \rightarrow tH \ (H \rightarrow \gamma \gamma)$

Submitted to JHEP

**Common tools for $H \rightarrow \gamma \gamma$ analysis**

- **Photon Reconstruction**
- **Vertex Selection**
- **Photon and diphoton identification**
- **Event Categorization**
- **Statistical Analysis**

$T \rightarrow tH \ (H \rightarrow \gamma \gamma)$

**Hadronic ($t \rightarrow bq\bar{q}$)**

- Minimum $\chi^2$ Method
- Quadratic Equation

**Leptonic ($t \rightarrow bl\bar{v}$)**

- BDT (NRE)
- BDT (SMH)

**Top Reconstruction**

**MVA Training**

- **SR Optimization**

**Modeling**

- **Limit extraction**

*Separate trainings are performed for three $T'$ mass categories: [600, 625, 650, 675, 700] [800, 900, 1000] [1100, 1200]

Analysis uses $H \rightarrow \gamma \gamma$ as a probe to tag $T'$

Define signal window: $m_{\gamma \gamma} \in [115, 135]$ GeV

**CMS Preliminary**

- $m_H = 125.36$ GeV
- $\mu = 1.03$

- All Categories
- $S/B$ fit
- $S/B$ weighted

**HIG-19-015**

$137 \text{ fb}^{-1} (13 \text{ TeV})$

$B$ component subtracted

$S/(S+B)$ Weighted Events / GeV
\( T \rightarrow tH \ (H \rightarrow \gamma \gamma) \)

Submitted to JHEP

- **Di-photon**
  - Flashgg preselected diphoton
  - \( P_T \) (leading photon) > \( M_W / 3 \)
  - \( P_T \) (subleading photon) > \( M_W / 4 \)
  - Photon ID MVA score > -0.7
  - 100 GeV < \( M_W \) < 180 GeV

- **Electron**
  - \( P_T > 10 \) GeV
  - \(|\eta| < 2.4\) with [1.4442, 1.566] excluded
  - Loose cut-based electron ID
  - \( \Delta R \) (electron and photon) > 0.4
  - \( \Delta M \) (electron/photon and Z) > 5 GeV

- **Muon**
  - \( P_T > 10 \) GeV and \(|\eta| < 2.4\)
  - Tight cut-based muon ID
  - Isolation < 0.25
  - \( \Delta R \) (muon and photon) > 0.4

- **Jets**
  - \( P_T > 25 \) GeV and \(|\eta| < 4.5\)
  - Tight ID (17/18) and Loose ID (16)
  - \( \Delta R \) (jet, photon/lepton) > 0.4
  - For \( w \)-jets, \(|\eta| < 3.0\)

- **bJets**
  - Loose working point of deepCSV
  - \( b \)-tagged discriminant is reshaped

- **Triggers**
  - 2016: \( \text{HLT\ Diphoton30\_18\_R9Id\_OR\_IsoCalold\_AND\_HE\_R9Id\_Mass80}^* \)
  - 2017: \( \text{HLT\ Diphoton30\_22\_R9Id\_OR\_IsoCalold\_AND\_HE\_R9Id\_Mass90}^* \)
  - 2018: \( \text{HLT\ Diphoton30\_22\_R9Id\_OR\_IsoCalold\_AND\_HE\_R9Id\_Mass90}^* \)
\( T \rightarrow tH \ (H \rightarrow \gamma \gamma) \)

Submitted to JHEP

- Multivariate analysis technique
  - Distinguish VLQ signal from background events
  - Gradient boosted decision trees (BDT)
  - Separate trainings are performed for three \( T' \) mass categories
    \([600, 625, 650, 675, 700]\) \([800, 900, 1000]\) \([1100, 1200]\)

- Leptonic channel
  - One BDT is trained for each \( T' \) mass category
  - Signal: VLQ
  - Background: \( t\bar{t}H, ggH, VH, VBF, tHq \)

- Hadronic channel
  - Two BDTs are trained for each \( T' \) mass category
  - Signal: VLQ
  - Non-resonant background (NRB): \( \gamma\gamma + \text{jets} \), data-driven QCD, \( t\bar{t}\gamma\gamma, t\bar{t}\gamma + \text{jets} \), \( t\gamma + \text{jets} \), \( t\bar{t} + \text{jets} \), \( V + \gamma \)
  - SM Higgs background (SMH): \( t\bar{t}H, ggH, VH, VBF, tHq \)
Pair production $TT/BB$

Accepted by JHEP

single-lepton channel
Pair production $TT/BB$

Accepted by JHEP

same-sign charge (SS) dilepton channel
Pair production $TT/BB$

multilepton channel with at least three leptons
Diboson pairs in all-jet final state

Accepted by Phys. Lett. B

Event categorisation

- 2 orthogonal main categories
  - VBF & gg/DY
  - Each of them divided in
    - VH: H-tag enriched (H/Z\to bb) 2D MD-deepAK8 ZHbbvsQCD
      - HPHP, HPLP, LPHP
    - VV: V-tag enriched (V\to qq) 2D MD-deepAK8 WvsQCD
      - HPHP, HPLP

- Subcategories defined by the purity (mistag rate) of the tagging:
  - HP = High Purity & LP = Low Purity

- Working points and categories prioritization optimized for WW and ZH
- Checked Punzi Significance and expected limits (including SF)